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(54) Title: FILM NOISE REDUCTION BY APPLICATION OF BAYES THEOREM TO POSITIVE/NEGATIVE FILM

(57) Abstract

At least one frame of a strip of photographic film is exposed to an image, and, prior to being developed, six (or so) calibration strips in a specially reserved frame on the same film are individually exposed to six predetermined calibration light sources producing six progressively increasing exposure levels spanning the exposure latitude of the film. A film layer develops a positive image in one color and a negative image in another color using positive and negative dyes, respectively. The film is scanned to determine the positive and negative dye amounts, D_p and D_n at each scanner pixel. The likeliest exposure value $\bar{E}$ as a function of D_n and D_p is determined probabilistically from six histograms obtained by scanning the six calibration patches on the film, all of the $\bar{E}$'s thus obtained being stored in a look-up table addressed by the corresponding values of D_p and D_n. The images recorded on the film are then scanned pixel-by-pixel, the D_p and D_n of each pixel addressing the look-up table to obtain the likeliest exposure value $\bar{E}$ for that pixel, which is then furnished to a printer. By thus combining the positive and negative images on the film, film noise is reduced in the resulting image to obtain the likeliest exposure value $\bar{E}$ at each pixel with the smallest error possible, with no prior knowledge of the film characteristics.

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FILM NOISE REDUCTION BY APPLICATION OF
BAYES THEOREM TO POSITIVE/NEGATIVE FILM

5 TECHNICAL FIELD

This invention is related to processes for
improving images obtained from photographic film and
in particular to reducing film noise in the
photographic images so obtained.

10   BACKGROUND OF THE INVENTION

Main Problem

Noise attributable to innate
characteristics of photographic film limits the
quality of images obtainable from photographic

15 film. The major source of such noise is random
variations in the density of silver halide grains
across the surface of a film emulsion layer. If the
film is divided into many picture elements
("pixels") which are sampled individually, each

20 pixel will have a different number of silver halide
grains. Such random variations in the number of
silver halide grains in each "pixel" on the film
causes different pixels to respond differently to
the same incident light. Upon chemical development,

25 pixels with more grains develop higher dye
densities. These pixel-by-pixel variations in
density appear as granularity. This can be thought
of as random pixel-to-pixel variations in
sensitivity--pixels with more grains are more

30 sensitive, having a higher response to the same
incident light.

However, by independently developing and
digitally scanning both latent and non-latent silver
halide grains in each pixel, the total number of

35 grains in each pixel can be determined. Using this

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information, the random variations in the number of
grains per pixel on film may be compensated by
simply normalizing or dividing the number of latent
(or non-latent) grains counted in a given pixel by
5 the total number of latent and non-latent grains in
that pixel.

        Typically, using a single dye (positive or
negative), scanning the film yields either the
number of non-latent grains or the number of latent
10 grains in each pixel, but not both numbers. In
order to obtain both numbers, two different color
dye are used, one dye responsive only to the
non-latent grains and the other dye responsive only
to the latent grains. By developing the same film
15 with both dyes, and by scanning the film with two
different color filters tuned individually to each
of the two dyes, the scanner can separately count
the number of latent and non-latent crystals in the
film. Such a process is described in detail by
20 Bird, "Normal Development, Reversal Development, and
Composite Processing: A New Method for Gaining a
Simultaneous Improvement in Latitude and Detective
Quantum Efficiency in Silver Halide Films,"
Photographic Science and Engineering, Vol. 22, No.
25 6, pages 328-335, November/December, 1978
(hereinafter referred to as "Bird"). The Bird
reference proposes an algorithm for combining the
densities of D_n and D_p by individually weighting
them and then computing the exposure from the
30 combination. The Bird algorithm optimizes the
detective quantum efficiency (the ratio between the
input noise and the output noise of the process)
requiring certain assumptions in film
characteristics, the main assumption being an
35 idealized monodisperse emulsion in the film. This

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assumption means that the silver halide grains are
of identical size throughout the emulsion so that
each grain: (1) presents the same photon absorption
cross-section "area", (2) requires the same number
5 of photons in order to become latent, (3) lies at
the same height as all other grains in the emulsion
so as not to obscure one another, and (4) produces
the same amount of dye.
Secondary Problem
10   The foregoing assumption clearly cannot be
relied upon in processing real film. Therefore, the
process, as described in the Bird reference above,
introduces errors or noise into the resulting
reconstructed image. This is because the process
15 does not take into account secondary sources of
noise in real film, specifically the
non-monodisperse nature of the real film emulsion.
The grains in such a real emulsion do not have the
same photon absorption cross-section, do not require
20 the same number of photons for becoming latent, do
not lie at the same height in the film layer, and
produce different amounts of dye. Thus, known
processes, such as that described in the Bird
reference, for reducing film noise introduce
25 additional sources of error attributable to
secondary noise sources in the film.
                    PROBLEM TO BE SOLVED
          What is needed is a process for reducing
film noise attributable to random variations in the
30 density of active grains across a film emulsion
without requiring prior assumption of film
characteristics, and which is therefore less
affected by any of the sources of film noise
discussed above. In the present invention, it is
35 recognized that the prior approach to solving this

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class of problems was unworkable. This approach was
based upon trying to understand the sources of noise
in film, to mathematically model them, and then by
some mathematical technique invert the process to
5   remove the noise. The Bird reference is an example
of this approach in which only the primary source of
noise was considered while the secondary sources
were ignored.

In the present invention, a different
10   approach is taken, namely to eschew any
understanding of the sources of noise in film or any
attempt to mathematically model them, and instead
process the data from the positive and negative dye
images in such a manner as to automatically take
15   into account all sources of noise without having to
understand them. The advantage of such an approach
is that it does not depend upon the simplifying
assumption of the algorithm proposed in the Bird
reference (namely the assumption of a monodispersive
20   emulsion), and therefore can be used with a real
film.

SUMMARY OF THE INVENTION

A user exposes the frames on a roll of film
to a number of scenes, but the last frame on the
25   roll of film is reserved for calibration purposes.
Before the roll of film is developed, the last frame
is divided into six patches and the six patches are
exposed to six different predetermined exposure
levels comprising a set of six exposure levels
30   spanning the estimated film latitude. (The number
of calibration patches is arbitrary.) If the film
comprises more than one emulsion layer (such as
color film), then one (or more) emulsion layer is
developed using positive and negative dyes of
35   different colors responsive to the non-latent and

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latent grains in the film, respectively. A scanner,
such as a CCD imager, scans each of the six
calibration patches twice, on the first pass through
a filter tuned to the color of the positive dye and
5   on the second pass through a filter tuned to the
color of the negative dye.

During the first pass, the scanner measures
the dye amount from the non-latent grains in each
pixel in each calibration patch, and during the
10   second pass measures the dye amount from the latent
grains in each pixel in each calibration patch.
From the dye amount measurements thus produced by
the scanner, six histograms are constructed, one for
each of the six calibration patches. Each histogram
15   represents the distribution of the number of pixels
as a function of the dye amount per pixel of
positive and negative dye sites sensed by the
scanner.

Each of the histograms is treated as a
20   graph of the probability that, given a particular
exposure level E, any pixel will develop a certain
positive dye amount D_p and a certain negative dye
amount D_n. The six histograms, which will now be
referred to as probability distributions, are stored
25   in memory.

Each user image on the film is now
scanned. The most probable exposure value for each
pixel in a user image is computed from the six
probability distributions previously obtained. The
30   following is one way for performing the computation
in accordance with the invention: The positive and
negative dye amounts D_p and D_n of a particular
user image pixel sensed by the scanner are
observed. Then, the six probability distributions
35   are each evaluated at the observed values of D_n

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and D_p to yield six corresponding probabilities.
Each of the six probability values thus obtained is
then multiplied by the exposure value of the
corresponding one of the six calibration patches to
5   obtain a weighted exposure value. The six weighted
exposure values thus obtained are added together and
the resulting sum is divided by the sum of all six
probability values to obtain the most probable
exposure value of the image pixel in question. In
10 proper statistical language, this is not precisely
the "most probable" exposure, but rather is the
"mean" exposure, which often is more desirable. The
foregoing is repeated for each pixel in a frame on
the film containing the exposed user image. The
15 likeliest exposure values thus computed are fed to a
printer which generates the user image.

            The foregoing process is a simplification
of the general process of this invention.

            In the preferred embodiment of the
20 invention, a more sophisticated algorithm is used
for accurately interpolating a continuum of exposure
values among the six calibration exposures, which
takes into account the different probability
distributions involved. Furthermore, an a priori
25 probability that a pixel will receive a certain
exposure E is determined and accounted for in the
preferred algorithm.

                    GAUSSIAN INTERPOLATION

            For computation of exposure values lying
30 between successive ones of the six calibration
exposure levels, the preferred embodiment of the
invention includes a unique interpolation process
which is as follows:

            The mean values of D_n and D_p, their
35 variances and their covariances are computed for

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each of the six probability distributions derived
from the six calibration patches. If the scanner is
an eight-bit CCD Scanner (for example), a likely
choice is to divide the exposure scale defined by
5   the six calibration exposures into 256 exposures.
The mean, the variance and the covariance of D_n
and of D_p are each plotted against the six
calibration exposure values and interpolated at 256
points along the exposure scale. Preferably, a
10   well-known method of interpolation using cubic
splines is employed. This produces 256 interpolated
values of the mean, the variance and the
covariance. From these, 256 new probability
distributions are constructed from each of the 256
15   sets of mean, variance and covariance values by
simply assuming that the new probability
distribution at each one of the 256 interpolated
points is multivariate-Gaussian. Each of the
Gaussian probability distributions is, in accordance
20   with well-known principles, uniquely defined by the
corresponding mean, variance and covariance at the
corresponding one of the 256 interpolated exposure
values.
         Next, the image processing algorithm
25   described in the previous sub-section above is
performed but, instead of using the six probability
distributions obtained from the six calibration
patches, the 256 new probability distributions are
used. The likeliest exposure value for a given user
30   pixel is computed as a weighted sum over all 256
probability distributions, resulting in a
"likeliest" exposure value.
Exposure Probability Distribution
         In a further refinement of the preferred
35   embodiment of the algorithm, each of the probability

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distributions, corresponding to a given exposure
level, is first multiplied by the probability of
receiving that exposure value before it is used in
the algorithm. The probability of receiving a given
5   exposure level is computed a priori from a large
collection of representative photographs or images.
For example, a large collection of consumer
photographs may be scanned if the user image is to
be processed for consumer type images. On the other
10 hand, in order to process astronomical images, a
large collection of astronomical photographs may be
scanned to compute the required exposure
probabilities.

SCRATCH DETECTION AND SUPPRESSION

15   The algorithm may also be used to locate
defective pixels, such as from scratches or dust.
Whenever a particular pixel is detected with joint
positive and negative dye amounts D_p and D_n
yielding a very low probability when substituted
20 into each of the probability distributions (such as
those constructed from the calibration patches),
that pixel is designated as a defective pixel.

        A scratch suppression algorithm may then be
employed. In one such scratch suppression
25 algorithm, for each pixel recognized as being
defective, the suppression algorithm defines a small
neighborhood of pixels around the defective pixel.
It searches that neighborhood for any non-defective
pixels, and keeps enlarging the neighborhood until
30 it finds at least one non-defective pixel in the
neighborhood. It then computes the median of all
the non-defective pixels in the neighborhood, and
replaces the original defective pixel by this median.

ADVANTAGE OF THE INVENTION OVER THE PRIOR ART

35   The probability distributions obtained from

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the calibration patches characterize all noise
sources present in that film, as well as in the
scanner. These noise sources include random
variations in grain density, random variations in
5   grain size, random variations in photon absorption
cross-section per grain, random variations in number
of photons required to transform a grain to
non-latency from latency, and variations in grain
height in the emulsion causing some grains to
10 obscure other grains, and even effects occurring
only after development such as dye clouds obscuring
other dye clouds and variations in the dye per
grain. To the extent that the film response is
statistically uniform everywhere on the strip of
15 film, the probability distributions obtained from
the calibration patches accurately reflect all of
the foregoing noise sources. Thus, the image
processing algorithm of the invention requires
absolutely no knowledge whatsoever of the film
20 characteristics prior to execution of the
algorithm. (The only exception is that the
progression of exposure values of the plural
calibration patches should span the exposure
latitude of the film.) Thus, the algorithm makes no
25 assumptions about grain size distribution,
variations in the number of grains per pixel, fog
levels, stain levels, non-linearity in the
development process, photon thresholds of the grains
or many other sources of noise. It does not depend
30 upon any mathematical model to explain the behavior
of the film, but instead relies on the calibration
patches to provide an empirical "understanding" of
the film.
        It can be shown mathematically (based on
35 Bayes' Theorem) that the algorithm of the present

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invention provides the estimate with the minimum
mean squared error for the exposure level of each
pixel, and any other algorithm will result in a
larger mean squared error. It is in this sense that
5 the algorithm of the invention is optimal.

DESCRIPTION OF THE DRAWINGS

The invention may be understood by
reference to the accompanying drawings of which:

Fig. 1 is a block diagram illustrating the
10 joint positive and negative development process of a
film bearing a series of calibration patches;

Fig. 2 is a diagram illustrating the
generation of an individual probability distribution
from each one of the calibration patches on the film;

15   Fig. 3 is a graph illustrating the
cross-sections of the probability distributions
obtained from all the calibration patches on the
film;

Fig. 4 is a block diagram illustrating the
20 image processing algorithm of the invention using
the probability distributions of Fig. 2;

Fig. 5 illustrates a refinement of the
algorithm of Fig. 4 in which the several probability
distributions of Fig. 2 are interpolated to generate
25 many probability distributions;

Fig. 6 illustrates the type of results
obtained from the interpolation of Fig. 5;

Fig. 7 is a block diagram illustrating the
preferred embodiment of the invention;

30   Figs. 8a-8d illustrate cross-sections at
four selected amplitudes of the probability
distributions obtained from histogramming the
calibration patches on a real film;

Figs. 9a-9d illustrate the actual results
35 obtained by interpolating between the probability

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distributions of Figs. 8a-8d; and

Figs. 10a-10d illustrate the interpolated probability distributions of Figs. 9a-9d at the same exposures as Figs. 8a-8d to demonstrate that the
5 interpolated data resembles the original data.

DETAILED DESCRIPTION OF THE INVENTION

Film Calibration

Referring to Fig. 1, a roll of film 100 may have, for example, 36 frames. In the present
10 invention, the user is allowed to take pictures on the first 35 frames, the 36th frame being reserved for use by the film development lab and is therefore not exposed by the user. (Alternatively, it may be exposed during manufacture, or by a special device
15 within the camera.) When the film 100 is received by the film development lab, frame 36 is divided into a number of patches (for example, six patches), each patch being exposed to a different predetermined exposure level from a calibrated light
20 source 105. One way of doing this is to simply lay a six exposure level gray scale mask 110 over frame 36 and then activate the calibrated light source 105.

Joint Positive and Negative Image Development
25 The film 100 is then developed using a special joint positive-negative image development process. If the film 100 is, for example, color film, it essentially comprises three different color layers. In one realization of this invention, only
30 one film layer (usually the top, green layer) is subjected to the joint positive-negative image development process, the remaining two layers being developed using ordinary processing techniques. The joint positive-negative image development process of
35 the invention is illustrated in Fig. 1 and is as

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follows:

The top film layer is first developed by a
partial latent grain developer 120 which develops
only a fraction of the latent grains in the top
5   layer of the film 100. Latent grains, as the term
is employed in this specification, are those silver
halide crystals which have absorbed enough photons
during the exposure of the film to experience a
chemical change. The partial grain developer 120
10 creates a dye of one color (for example, cyan),
which colors the film at each latent grain site
developed by the developer 120. The result is a
negative dye density D_n which varies across the
top layer of the film 100 so as to define a negative
15 cyan color image. Thereafter, a black and white
latent grain developer 122, creating no color dyes,
develops the remaining latent crystals which were
not developed by the partial latent grain developer
120. Thus the latent grains have been developed to
20 yield a negative dye density D_n defining a cyan
negative image.

The film is then processed with a
non-latent grain developer 124 which develops all of
the non-latent grains in the top layer of the film
25 100 creating a different colored positive dye (for
example a magenta dye) so that all of the non-latent
grain sites in the top layer of the film 100 are
marked by a magenta dye spot. Non-latent grains, as
the term is employed in this specification, are
30 those silver halide crystals in the top layer of the
film 100 which have not absorbed a sufficient number
of photons during the exposure of the film to
experience a chemical change to make them responsive
to the previous developers 120 and 122. The result
35 is a positive dye (magenta) density D_p which

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varies across the top layer of the film 100 to
define a magenta colored image.

Thus, the top layer of the film 100 bears
two images of different colors, a negative cyan

5   image and a positive magenta image. The result is
illustrated in the developed film strip 100' in Fig.
7. Each of the six calibration patches in frame 36
also has a cyan negative image and a magenta
positive image of generally uniform density across

10 the patch. Generally, as the cyan density increases
from patch to patch, the magenta density decreases.

The problem now is how to overcome the
effect of film granularity which degrades the
quality of the user images in frames 1-35.

15 Computing the Conditional Probability
Functions of Joint Dye Densities for
Each Exposure Level

Each of the six calibration patches in
frame 36 is now used to construct the probability

20 function of the joint positive and negative dye
densities D_n, D_p for each of the six exposure
levels. This is done as follows: An electronic
image scanner 200 such as a CCD imager scans each of
the six calibration patches in frame 36, one at a

25 time. The scanner 200 views each calibration patch
as simply a plurality of pixels, the number of which
depends upon the resolution of the scanner 200. The
scanner 200 first views the calibration patch in
question through a green filter (complementary to

30 magenta) so as to detect the positive dye density
D_p at each pixel. Then the scanner 200 views the
calibration patch through a red filter
(complementary to cyan) so as to detect the negative
dye density D_n at each pixel. The scanner 200

35 observes each of the positive and negative dye

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densities D_p, D_n as the brightness of a
particular pixel when viewed through a green or red
filter respectively. The data thus obtained from
the scanner for each calibration patch (exposure

5   level) is combined as a histogram for that exposure
level, defining the number of pixels sensed by the
scanner 200 having a particular joint density value
D_p, D_n. The results are plotted in Fig. 2, in
which the data created by the scanner 200 from each

10 of the six calibration patches of frame 36 yields a
three-dimensional "bell" curve, the two horizontal
axes corresponding to values of D_n and D_p
respectively, and the vertical axis corresponding to
the number of pixels at each joint value D_n,

15 D_p. In this invention, each of these histograms
is viewed as the conditional probability
distribution for finding a joint dye density value
D_p, D_n given a particular exposure value E_i.
In this example, there were six calibration patches

20 so there are six conditional joint probability
distribution functions, as illustrated.

A cross-section 3-3 of each of the six
joint probability distribution functions of Fig. 2
may be taken at a chosen amplitude, say 10% of the

25 maximum number of pixels counted by the scanner
200. Each of these cross-sections may then be
superimposed as illustrated in Fig. 3, in order to
provide an understanding as to how the joint
probability distributions differ among the six

30 exposure values of the calibration patches of frame
36 in Fig. 2.

The scanner 200 may be thought of as a CCD
imager characterized by a square array of
photon-collection sites, comprising n rows and n

35 columns of such sites. Each site defines one pixel,

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so that there are n^2 pixels in the imager. In one
embodiment of the invention, the scanner takes one
"snapshot" of each calibration patch through the red
filter and then one shot of each calibration patch
5   through the green filter to generate the data
required. If the signal created at each of the
photon-collection sites in the scanner 200 is
converted by an analog-to-digital converter to an
eight-bit byte, then each pixel has a dynamic range
10   from 0 to 255 units. In this case the units specify
the minimum and maximum detectable values of the
negative and positive dye densities D_n, D_p.
Thus, each of the six pairs of horizontal axes
labeled D_n and D_p of Fig. 2 extend from
15   normalized dye density values 0 through 255. The
vertical axis represents the percentage of the total
number of pixels. In this example, the total number
of pixels is n^2. Typically, in CCD imagers
suitable for the present application, n^2 is on the
20   order of half a million pixels.

The data representing each of the six joint
probability distributions illustrated in Fig. 2 is
stored in memory. In this application the data
characterizing each of the six joint probability
25   distributions illustrated in Fig. 2 may be thought
of as an XY addressable memory, in which the X axis
corresponds to the 256 possible values of D_n, the
Y axis corresponds to the 256 possible values of
D_p and the data stored in each of the X, Y
30   locations in the memory are the corresponding pixel
counts from the scanner 200. Such an X, Y array of
data shall be denoted in this application $P(D_p,$
$D_n \mid E_i)$, using conventional notation from
statistical mathematics. P is the conditional
35   probability value that, given a particular exposure

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value E_i, a pixel selected at random will be found
to have a particular joint positive and negative dye
value D_p, D_n. Each joint probability
distribution function illustrated in Fig. 2 is
5 labeled using this same notation.

Computation of the Probability of Having
Received a Particular Exposure Value Given a
Certain Joint Dye Density Value D_n, D_p
10   The six joint probability distributions
$P(D_p, D_n | E_i)$ generated for the six calibration
exposures may be used in combination to infer the
related conditional probability $P(E_i | D_p, D_n)$.
In accordance with conventional notation, the latter
15 is the probability that, given an observed joint
positive and negative dye density value D_n, D_p,
a particular exposure value E_i was received by the
pixel in question. Given that a particular joint
dye density value D_n, D_p is observed at a given
20 pixel, the question is: what is the probability
that that particular pixel received a certain
exposure value E_i? This quantity is
$P(E_i | D_p, D_n)$.
       The answer to this question is obtained
25 using the well-known Bayes theorem of statistical
mathematics. One additional piece of information is
needed, the a priori probability for a given
exposure E_i, designated $P(E_i)$. This is the
probability that the pixel has received exposure
30 E_i, based on no knowledge of D_p, D_n. This may
be obtained by histogramming many typical
photographs. Then according to Bayes theorem, the
probability that one of the six exposures E_1, ...,
E_6 was received by the pixel is:

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$$P(E_j | D_p, D_n) = P(D_p, D_n | E_j) \, P(E_j) / \sum_{i=1}^{6} P(D_p, D_n | E_i) \quad (1).$$

By interpolating 256 exposures among the measured
six exposures (Fig. 5), exposure E_j may be
determined with greater resolution.

5   This result may be used to enhance the user
images stored in frames 1-35 of the film 100, as
follows:

Computation of the Most Probable
10   Exposure Value from a Given Joint Dye Density
Value D_n, D_p
         The most probable (or more accurately the
"mean") exposure value may be computed for each
joint dye density value D_p, D_n observable by the
15   scanner 200, and this value shall be labeled herein
$\bar{E}$ (D_p, D_n), or simply $\bar{E}$.

         For a particular pixel, $\bar{E}$ is the normalized
sum of the six calibration exposure values E_i (for
20   all i from 1 through 6) individually weighted
(multiplied) by the probability amplitudes
$P(E_i | D_n, D_p)$ (as defined above in equation 1)
evaluated at the observed joint dye density value
D_p, D_n of the particular pixel. Using the
25   definition of equation 1, this weighted sum is:

$$(2) \quad \bar{E} \, (D_p, D_n) = \sum_{i=1}^{m} E_i \, P(D_p, D_n \mid E_i) \, P(E_i) /$$

$$\sum_{i=1}^{m} P(D_p, D_n \mid E_i) \, P(E_i).$$

30   The evaluation of the six probability
distribution functions at each of the 256^2
possible joint density values D_p, D_n (assuming
the scanner 200 has an eight-bit resolution)

35

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requires 256^2 different computations using

equation 2. The result is 256^2 values of $\bar{E}$

·associated with corresponding ones of the 256^2

possible joint dye density values D_p, D_n. As

5 illustrated in Fig. 4, these results are

stored in a look-up table in which a most probable

(mean) exposure value $\bar{E}$ is stored in a location

addressed by the corresponding joint dye density

value D_p, D_n. The look-up table 300 is the key

10 in processing each of the user images in frames 1-35

of the film 100 through the scanner 200. For better

precision, the six exposures E_i are replaced by

the 256 interpolated exposures.

Joint Positive-Negative Dye Image Enhancement of

15 User Images

Now the scanner 200 scans a given one of

the user images stored in one of the frames 1-35 of

the film 100. Each pixel in a given user image is

determined by the scanner 200 to have a certain

20 positive dye density D_p and a certain negative dye

density D_n, each of these dye densities lying

somewhere between a value of 0 and 255, assuming the

scanner has eight bits of resolution. For each

pixel, the scanner 200 transmits the observed joint

25 dye density value D_p, D_n to the address input

300a of the look-up table 300. The look-up table

300 responds (in the manner of a programmable read

only memory) by transmitting the corresponding

likeliest exposure value $\bar{E}$ at its data output 300b.

30 A succession of likeliest exposure values defining

an enhanced version of the user image is thus

transmitted in an order determined by the scanner

200 to an output device such as a printer.

REDUCTION OF NOISE

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It is clear that obtaining independent
images from the latent and non-latent grains in the
film provides more information from a given image
exposure than development of only one or the other
5   of the positive and negative images. With this
additional information, it is clear that the noise
in the resulting image should be reduced. The
question is how to combine the information from the
positive and negative images without introducing new
10   sources of noise or distortion. It can be proven
mathematically that the algorithm described above
computes a probable exposure value for each scanned
pixel in the film with the minimum mean squared
error theoretically possible, and that any other
15   method will result in a larger mean squared error in
the computed exposure value. Equations 1 and 2 are
the direct result of Bayes theorem in statistics,
and may be simplified as follows:

$$(3) \quad P(E|D_p, D_n) \quad = \quad \frac{P(D_p, D_n|E)}{\sum_i P(D_p, D_n|E_i)}$$

20

$$(4) \quad \bar{E} \quad = \quad \frac{\sum_i E_i \, P(D_p, D_n|E_i)}{\sum_i P(D_p, D_n|E_i)}$$

25   The simplification of equations 3 and 4 from
equations 1 and 2 is obtained by assuming $P(E)$
(which is the a priori probability that a given
exposure level will be received) is the same for all
exposure values--and is therefore conveniently
30   defined to be unity. This results in only a small
degradation in the performance of the algorithm.
In a more complex embodiment of the
invention, $P(E)$ is not uniform and is inferred from
a large collection of photographs from consumer
35   images (if consumer film is to be processed) or

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astronomy images (if astronomical photographs are to
be processed), etc.

<div align="center">GAUSSIAN INTERPOLATION OF THE

JOINT PROBABILITY DISTRIBUTIONS</div>

5   ·   From equation 2, it is apparent that in

most cases the likeliest exposure value $\bar{E}$ will lie
somewhere between various ones of the six
calibration exposure values (used to generate the
calibration patches of frame 36 of the film 100),

10   and therefore should be properly interpolated.
Experimental results obtained using this invention
indicate that the joint probability distribution
functions such as those illustrated in Fig. 2
(obtained from the calibration patches) are

15   approximately Gaussian in nature. Therefore, for a
more accurate computation of likely exposure values

$\bar{E}$ which lie between adjacent ones of the six
calibration exposure values, a large number of
"interpolated" probability distribution functions,

20   lying (in the D_p, D_n plane) between the six
probability distribution functions illustrated in
Fig. 2 are generated using an interpolation method
based upon the Gaussian nature of the probability
distribution functions of Fig 2.

25   The interpolation process is illustrated in
Fig. 5 while the results are partially illustrated
in a cross-sectional view in Fig. 6 corresponding to
that of Fig. 3. In Fig. 6, the six probability
distributions generated from the six calibration ·

30   patches are illustrated in cross-section in solid
line. An interpolated probability distribution
lying between each adjacent pair of solid line
probability distributions is illustrated in dashed
line in Fig. 6, the interpolated (dashed line)

35

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probability distribution having been obtained using
the interpolation process of Fig. 5.

In the preferred embodiment of the
invention, 256 interpolated probability distribution
5   functions (not shown in Fig. 6) are generated
corresponding to 256 exposure values lying in the
range of the minimum and maximum calibration
exposure values E_1 and E_6. Preferably, E_1 and
E_6 substantially span the exposure latitude of the
10   film 100.

As illustrated in Fig. 5, the following
process is performed for each of the six probability
distribution functions illustrated in Fig. 2.
First, the mean value of the negative dye density,
15   $\overline{D}_n(E_i)$ at the ith one of the six calibration
exposures is computed from the ith probability
density function in accordance with equation (a)
illustrated in Fig. 5. Six such mean values

$\overline{D}_n(E_i)$ are thus obtained for each of the six
20   values from of i from 1 through 6. When these six
values are plotted, the result is the graph

illustrated in Fig. 5 of $\overline{D}_n$ vs. E. The same
process is performed using equation (b) to compute

25   the six mean values $\overline{D}_p(E_i)$, which generate six
data points illustrated in the corresponding graph

of $\overline{D}_p$ vs. E in Fig. 5. The variance $S_{nn}(E_i)$
is computed in accordance with equation (c) in Fig.
5 for each of the six probability distribution
30   functions of Fig. 2, resulting in the corresponding
graph of S_{nn} vs. E in Fig. 5. In accordance with
equation (d), the variance of the positive dye
density values $S_{pp}(E_i)$ similarly is computed,
which results in the graph of S_{pp} vs. E in Fig.
35

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5. Finally, the covariance S_{pn} of the positive
and negative dye density values is computed in
accordance with equation (e) of Fig. 5 for each of
the six probability density functions of Fig. 2,

5   resulting in the corresponding graph in Fig. 5 of
S_{pn} vs. E.

If, for example, it is desired to compute
the likeliest exposure value $\overline{E}$ with eight-bit
resolution, then each of the graphs of Fig. 5 is

10 interpolated so that 256 data points lie in the
range from i=1 through i=6. The preferred method
for interpolation is interpolation using quasi-cubic
Hermite splines. The method is well-known and
commercial software is available for performing the

15 interpolation by cubic splines. The goal in
interpolating between the six data points in each of
the graphs above is to achieve the smoothest
possible curve which most truly represents the six
data points. The horizontal axes of each of the

20 five graphs of Fig. 5 may now be thought of as
having been divided into 255 equal segments
separated by 256 points, with an index j which runs
from 1 to 256, 256 points lying between the points
designated i=1 and i=6. For each value of j, the

25 corresponding values of $\overline{D}_n(E_j)$, $\overline{D}_p(E_j)$,
$S_{nn}(E_j)$, $S_{pp}(E_j)$, $S_{pn}(E_j)$ are "picked
off" the interpolated curves and a Gaussian
probability distribution is then constructed from
these five particular values in accordance with

30 equation (f) of Fig. 5. This process is repeated
for each value of j, so that 256 probability
distributions are computed in accordance with
equation (f). These are the interpolated
probability distributions. It is the interpolated

35

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probability distributions (from equation f of Fig.
5) which are now substituted into equation 2 in
place of the six original probability distributions
(computed directly from the six calibration patches)
5   to increase the exposure value resolution of the
algorithm of Fig. 4. With this change, the
summations in equation 2 (and in Fig. 4) are over
256 points (namely from i=1 to i=256) instead of
only six points as indicated in equation 2.

10   Equation f in Fig. 5 is the well-known
definition of the multivariate Gaussian probability
distribution for two variables, in this case D_n
and D_p. The $^{-1}$ superscript in equation f
indicates the inverse of a matrix, while the ^{T}
15   superscript indicates the transpose of a vector, in
accordance with standard notation.

SCRATCH SUPPRESSION

Many film defects, such as scratches,
pinholes and dust, result in unreasonable values of
20   (D_p, D_n). More precisely, "unreasonable" means
that the defect produces a joint density $(D_p,
D_n)$ for which the probability $P(D_p, D_n|E)$ is
very small for all possible values of E. Thus, by
slightly modifying the algorithm to watch for
25   unreasonable values of (D_p, D_n), the algorithm
can recognize many film defects.

A scratch detection algorithm and a scratch
suppression algorithm have been added (here the word
"scratch" is meant to be a generic word for the
30   defects that can be detected), which recognize
scratches as described above and suppress them. For
each pixel recognized as scratched, the suppression
algorithm defines a 3 x 3 neighborhood around the
defective pixel. It searches that neighborhood for
35   any non-defective pixels, and it keeps enlarging the

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neighborhood until it finds at least one
non-defective pixel in the neighborhood. It then
computes the median of all the non-defective pixels
in the neighborhood, and replaces the original
5 defective pixel by this median. This algorithm is
repeated for each defective pixel.

        The particular algorithm used for scratch
suppression is not so important as the fact that
scratches may be detected.

10   PREFERRED SYSTEM OF THE INVENTION (FIG. 7)

        In accordance with the foregoing detailed
description, the complete preferred system of the
invention is illustrated in Fig. 7. A scene viewed
through camera optics is recorded on film 100 as an
15 image 102. In addition, several calibration patches
104 are recorded on another portion of the film 100
using calibration light source 105 and a gray scale
step tablet 110. As described in more detail in
connection with Fig. 1 previously herein, joint
20 positive and negative developers 120, 122, 124
generates a joint positive and negative color image
from the film 100 corresponding to the recorded
scene image 102 and the calibration patches 104.

        The first step in the process of the
25 invention is for digital scanner 200 to scan the
plural calibration patches 104. As described
previously, each patch is first scanned through a
red filter and then through a green filter so that
it separately scans negative and positive images.
30 An isolation switch 400 routes the digital scanner
data of the calibration patches to a histogram
calibration patch processor 402 which forms plural
histograms in accordance with the previous
description given in connection with Fig. 2.
35 Specifically, if there are six calibration patches

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within the calibration patch area 104 on the film
100, then the histogram processor 402 produces six
histograms or probability distribution "clouds". An
interpolation processor 404 then interpolates the
5   six clouds to form 256 probability distribution
clouds corresponding to 256 exposure values lying
within the latitude of the film 100, in accordance
with the process described previously in detail in
connection with Fig. 5. These 256 probability
10   distribution clouds are each designated $P(D_p,$
$D_n|E_j)$, where the subscript j runs from 1
through 256.

Next, a large archive of old photographs
500 representative of the type of scene which is
15   expected to be recorded on the film 100 is scanned
by a digital scanner (such as the digital scanner
200). This scanning results in a histogram of the
number of times a particular exposure value is
observed. This produces a probability distribution
20   $P(E)$ that a particular exposure value will be
received. A Bayes theorem processor 600 performs
the computation of equation (1) stated above on page
17 using all of the 256 probability distributions
obtained from the interpolation processor 404 and
25   the probability distribution obtained from the
histogram processor 504. A best estimate (mean) of
exposure processor 602 performs the computation of
equation (2) stated above on page 18 using the
results obtained from the Bayes theorem processor
30   600 to provide a best estimate of exposure for each
joint value of positive and negative dye density
D_p, D_n. These results are stored in a look-up
table 300 in accordance with the detailed
description given previously in connection with Fig.
35   4.

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The system is now prepared to process the
image 102 on the film 100. The isolation switch 400
now routes the user image data from the digital
scanner 200 directly to the look-up table 300. For
5 each pixel in the image 102, the digital scanner 200
transmits a joint positive/negative dye density
D_p, D_n through the isolation switch 400 to the
address input of the look-up table 300. The look-up
table 300 matches each joint dye density D_p, D_n
10 thus received to the corresponding estimated

exposure value $\overline{E}$. The exposure value $\overline{E}$ thus
determined is transmitted to a printer 900, which
generates a corresponding image from the succession

of likeliest exposure values $\overline{E}$ thus obtained.
15   In accordance with the description of the
scratch suppression algorithm given on page 23 of
the detailed description, a scratch detection
processor 700 determines from the probability
distributions generated by the Bayes Theorem
20 processor 600 which joint dye densities D_p, D_n
correspond to unacceptably low probability
amplitudes for all possible exposure values E. A
scratch detection processor 700 causes all such
unacceptable joint dye density values to be flagged
25 in the look-up table 300. Thus, whenever such an
unacceptable joint dye density value is received by
the look-up table 300 from the digital scanner 200
(through the isolation switch 400), a flag is
automatically raised so that the corresponding
30 exposure values stored in the look-up table is not
transmitted, but instead a special "flag" value is
transmitted, and a scratch suppression processor 702
is activated. The missing exposure value is
provided by the scratch suppression processor 702 as

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follows: For each pixel recognized as scratched,
the suppression processor 702 defines a 3 x 3
neighborhood around the defective pixel. It
searches that neighborhood for any non-defective
5   pixels, and keeps enlarging the neighborhood until
it finds at least one non-defective pixel in the
neighborhood. It then computes the median of all
non-defective pixels in the neighborhood, and
replaces the original defective pixel by this
10 median. The scratch suppression processor 702
operates in the same manner for each flag recognized
from the look-up table 300.

In summary, the scratch detection processor
700 examines all the probabilities being computed in
15 Bayes theorem processor 600, and takes note of any
probabilities below threshold ("unreasonable"
values). It then replaces the likeliest exposure
value in the look-up table 300 with a special value,
called the "scratch flag" value. Now the look-up
20 table 300 is ready, and the image is passed from the
isolation switch 400 to the scratch suppression
processor 702 through the look-up table 300. The
scratch suppression processor 702 monitors the
values as they pass through. Any value which is not
25 the "scratch flag" value is passed unchanged. When
a "scratch flag" value is encountered, the scratch
suppression algorithm is triggered, which grows a
neighborhood and computes the median, and the
"scratch flag" value is replaced by the median.
30 Thus, for scratched pixels the look-up table 300
does not actually contain "likeliest exposure"
values, but instead contains a "scratch flag" value.

Other algorithms 800 may be performed on
the data before it is transmitted to the printer
35 900. Such other algorithms may include various

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image processes which are well-known in the art for
enhancing images.

EXPERIMENTAL RESULTS (FIGS. 8-10)

The invention has been applied to a real

5   film. This film is an ordinary, single layer
emulsion. A glimpse at the experimental results is
useful.

Fig. 8 shows the result of histogramming
the calibration patches for the film, specifically

10   the probability distributions $P(D_p, D_n|E)$
obtained from histogramming the calibration patches
on a real film. The lowest exposure patch is
plotted in red, the next higher exposure is plotted
in green, next in blue, next in red, ... Exposures

15   are separated by 0.3 log exposure (standard
granularity neutral density step tablet).
Overlapping locations are plotted in combined color
(yellow where red and green overlap, cyan where
green and blue overlap). $P(D_p, D_n|E)$ for a

20   single E is named a "cloud," since the edges are
fuzzy because of the decaying probability
distribution. Each of the four frames represents a
slice through the $P(D_p, D_n|E)$ at the percentage
of peak height shown. The horizontal axis is D_p,

25   the vertical axis is D_n.

The gross features are as expected, but
many of the details, such as the locus traced by
successive exposures, and the wide aspect ratio of
the clouds even at the very low and very high

30   exposures, are surprising. Fig. 9 shows the result
of interpolating new clouds (multivariate Gaussian
distributions). The figure shows 15 clouds for
clarity. The algorithm was actually run with 256
interpolated clouds, but this figure shows the case

35   of only 15 clouds for greater clarity.

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Fig. 10 illustrates the eight clouds of the
15 interpolated clouds that correspond to the
original measured eight clouds. These clouds are
included in the bottom plot, but are separated out
5   in the center plot for easier comparison with the
top plot. Note that for the frame tagged "> 0.0%",
the plot simply shows the cutoff for calculating the
multivariate normal $P(D_p, D_n|E)$ where the
probability is very low. In fact, a multivariate
10 normal distribution is everywhere larger than 0, so
in principle each cloud fills the entire frame.

Note that while the choice of using
multivariate normal distributions to represent the
clouds is arbitrary, it appears to be a reasonable
15 fit, and the results should be fairly insensitive to
the accuracy of this choice.

While the invention has been described in
detail with specific reference to preferred
embodiments thereof, it is understood that
20 variations and modifications thereof may be made
without departing from the spirit and scope of the
invention. In particular, there are other ways of

computing $\bar{E}$ from D_p, D_n, but equations 1 and 2
are the best possible.
25   SOFTWARE IMPLEMENTATION

A portion of the disclosure of this patent
document contains computer programs to which a claim
of copyright protection is made. The copyright
owner has no objection to the facsimile reproduction
30 by anyone of the patent document or the patent
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other rights whatsoever.

A Fortran program for implementing in a
35 general purpose computer the noise reduction process

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described with reference to Figs. 5 and 7 is listed
in Table I below with reference to the attached
appendices.

TABLE I

SOFTWARE PROGRAM	ATTACHED APPENDIX	CORRESPONDING FIGURE
MAKETABLE EXPOS 2D	APPENDIX A	FIG. 5
SCRATCH SUPPRESS	APPENDIX B	FIG. 7 (700, 702)

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CLAIMS:

1.   A method for obtaining an enhanced
image from a photographic film susceptible of
photographically recording in a frame thereof an
5   image comprising individual image pixels
characterized by individual latent and non-latent
photosensitive grain counts D_p and D_n
respectively, said method comprising:
obtaining a plurality of K distributions of
10   latent and non-latent grain count pairs D_p, D_n
for K predetermined exposure values, said K
distributions being at least approximately
characteristic of said film;
determining from said K distributions a
15   likeliest exposure value E_i for each one of a
plurality of grain count pairs D_p, D_n so as to
generate a corresponding plurality of likeliest
exposure values; and
measuring a grain count pair D_p, D_n in
20   a discrete pixel in said film frame and selecting
the corresponding one of said likeliest exposure
values so as to generate a set of likeliest exposure
values representative of the image recorded in said
film frame.

25.   2.   The method of Claim 1 wherein said
obtaining step comprises:
exposing a film strip to said K
predetermined exposure levels so as to form K
calibration patches in said film strip;
30   developing the latent and non-latent grains
in said calibration patches in such a manner that a
latent grain count D_p and a non-latent grain count
D_n in discrete pixels therein may be measured
separately;
35   measuring latent and non-latent grain count

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pairs D_p, D_n in each discrete pixel in said K
calibration patches so as to generate said K
distributions.

   3. The method of Claim 1 further
5 comprising the step of printing an image based on
said set of exposure values representative of said
image recorded in said film frame.

   4. The method of Claim 1 wherein said
measuring step is preceeded by the step of
10 developing the latent and non-latent grains in said
film frame in such a manner that a latent grain
count D_p and a non-latent grain count D_n in
discrete pixels therein may be measured separately.

   5. The method of Claim 2 wherein said film
15 strip and said film frame are on the same roll of
film whereby said developing steps are carried out
simultaneously in said calibration patches and in
said film frame, whereby latent and non-latent grain
counts are separately measureable in said film frame
20 as well as in said calibration patches, and whereby
said K distributions are exactly characteristic of
said film.

   6. The method of Claim 1 wherein said
determining step comprises:

25   defining a set of N exposure values E_j
wherein N > K, said N exposure values at least
partially coinciding with a range of exposure values
spanned by said K exposure values;

    computing a plurality of N distributions of
30 grain count pairs D_n, D_p for said N exposure
values from said K distributions; and

    determining from said N distributions said
likeliest exposure value for each one of said
plurality of grain count pairs D_p, D_n so as to
35 generate said corresponding plurality of likeliest

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exposure values.

      7. The method of Claim 6 wherein said computing step comprises interpolating between successive ones of said K distributions.

5   8. The method of Claim 6 wherein said N exposure values span an exposure latitude of said film strip.

      9. The method of Claim 1 further comprising the step of weighting said distributions

10 in accordance with a predetermined probability distribution of exposure values prior to said determining step.

      10. The method of Claim 9 wherein said predetermined probability distribution of exposure

.15 values defines the probability of any pixel in said frame being exposed to a given exposure value.

      11. The method of Claim 1 further comprising the step of detecting for each pixel of said frame whether a scratch is present after said

20 second measuring step, said method further comprising the step of foregoing said selecting step for any pixel in which said detecting step step detects a scratch and constructing an alternative exposure value by interpolating between the exposure

25 values of neighboring pixels.

      12. The method of Claim 11 wherein said detecting step comprises determining the probability of occurence of the grain count pair D_n, D_p measured in each pixel of said frame and flagging

30 the existence of a scratch whenever said probability is below a predetermined threshold value.

      13. The method of Claim 12 wherein said probability of occurence is computed for each one of a set of exposure values spanning an exposure

35 latitude of said film strip.

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14. The method of Claim 7 wherein said interpolating step comprises:

computing a mean value and a variance of D_n and D_p and computing a covariance of D_n

5   with D_p for each one of said K distributions so as to define K magnitudes of said mean value, variance and covariance corresponding to said K exposure values;

interpolating between said K magnitudes at

10   said N exposure values so as to define interpolated versions of each one of said mean value, variance and covariance at said N exposure values; and

constructing an interpolated Gaussian probability distribution of grain count pairs D_p,

15   D_n for each one of said N exposure values from the corresponding interpolated versions of said means values, variances and covariance for each respective one of said N exposure values.

15. The method of Claim 8 wherein each of

20   said K exposure values is defined by an m-bit binary word and wherein $N = 2^m$, whereby to utilize the full range and resolution with which said exposure values are defined.

16. The method of Claim 9 wherein said

25   weighting step computes a normalized weighted sum of said K distributions with said predetermined probability distribution in accordance with Bayes theorem.

17. The method of Claim 1 wherein said

30   developing step comprises developing said latent and non-latent grains sequentially using a different color dye for each.

18. The method of Claim 17 wherein said latent and non-latent grains are developed with

35   positive and negative dyes, respectively, or

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negative and positive dyes, respectively.

19.   The method of Claim 6 further
comprising the step of weighting said distributions
in accordance with a predetermined probability
5   distribution of exposure values prior to said
determining step.

20.   The method of Claim 19 wherein said
predetermined probability distribution of exposure
values defines the probability of any pixel in said
10   frame being exposed to a given exposure value.

21.   A system for obtaining enhanced images
from photographic film in which there has been
exposed a film frame to a scene so as to record an
image therein, said system comprising:
15   means for developing the latent and
non-latent grains in said film frame in such a
manner that a latent grain count D_p and a
non-latent grain count D_n in discrete pixels
therein may be measured separately;
20   means for storing a plurality of K
distributions of latent and non-latent grain count
pairs D_p, D_n for K predetermined exposure
values, said K distributions being at least
approximately characteristic of said film;
25   means for determining from said K
distributions a likeliest exposure value E_i for
each one of a plurality of grain count pairs D_p,
D_n so as to generate a corresponding plurality of
likeliest exposure values; and
30   means for measuring a grain count pair
D_p, D_n in each discrete pixel in said film frame
and selecting the corresponding one of said
likeliest exposure values so as to generate a set of
likeliest exposure values representative of the
35   image recorded in said film frame.

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22. The system of Claim 21 further comprising:

means for developing latent and non-latent grains in K calibration patches in a strip of film
5   which have been exposed to said K predetermined exposure levels in such a manner that a latent grain count D_p and a non-latent grain count D_n in discrete pixels in said calibration patches may be measured separately;

10   means for measuring latent and non-latent grain count pairs D_p, D_n in each discrete pixel in said K calibration patches so as to generate said K distributions, and for transmitting said K distributions to said means for storing.

15   23. The system of Claim 22 further comprising means for developing latent and non-latent grains in said film frame in such a manner that a latent grain count D_p and a non-latent grain count D_n in discrete pixels
20   therein may be measured separately.

24. The method of Claim 22 wherein said film strip and said film frame are on the same roll of film whereby said K distributions exactly characterize said film.

25   25. The system of Claim 21 further comprising means for printing an image based on said set of exposure values representative of said image.

26. The system of Claim 21 wherein said means for developing said grains in said calibration
30   patches and said means for developing said grains in said film frame are one and the same.

27. The system of Claim 21 wherein said means for determining comprises:

means for computing a set of N
35   distributions of grain count pairs D_n, D_p for a

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plurality of N predetermined exposure values,
wherein N > K, said N exposure values at least
partially coinciding with a range of exposure values
spanned by said K exposure values; and

5   means for determining from said N
distributions said likeliest exposure value for each
one of said plurality of grain count pairs D_p,
D_n so as to generate said corresponding plurality
of likeliest exposure values.

10   28. The system of Claim 27 wherein said
means for computing comprises means for
interpolating between successive ones of said K
distributions.

          29. The system of Claim 27 wherein said N
15 exposure values span an exposure latitude of said
film.

          30. The system of Claim 21 further
comprising means for weighting said distributions in
accordance with a predetermined probability
20 distribution of exposure values, said means for
weighting being connected to said means for
determining.

          31. The system of Claim 30 wherein said
predetermined probability distribution of exposure
25 values defines the probability of any pixel in said
frame being exposed to a given exposure value.

          32. The system of Claim 21 further
comprising means for detecting for each pixel in
said frame whether a scratch is present, said means
30 for detecting being connected to said means for
measuring, said system further comprising means for
foregoing said selecting step for any pixel in which
said detecting step step detects a scratch and
constructing an alternative exposure value by
35 interpolating between the exposure values of

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neighboring pixels.

      33. The system of Claim 32 wherein said means for detecting comprises means for determining the probability of occurence of a respective grain

5 count pair D_n, D_p measured in a respective pixel in said frame and flagging the existence of a scratch whenever said probability is below a predetermined threshold value.

      34. The system of Claim 33 wherein said

10 probability of occurence is computed by said means for detecting for each one of a set of exposure values spanning an exposure latitude of said film.

      35. The system of Claim 28 wherein said means for interpolating comprises:

15   means for computing a mean value and a variance of D_n and D_p and computing a covariance of D_n with D_p for each one of said K distributions so as to define K magnitudes for each mean value, variance and covariance corresponding to

20 said K exposure values;

      means for interpolating between said K magnitudes at said N exposure values so as to define interpolated magnitudes of said mean value, variance and covariance at said N exposure values; and

25   means for constructing an interpolated Gaussian probability distribution of grain count pairs D_p, D_n for each one of said N exposure values from the interpolated magnitudes of said means value, variance and covariance for each

30 respective one of said N exposure values.

      36. The system of Claim 29 wherein each of said K exposure values is defined by an m-bit binary word and wherein $N = 2^m$, whereby to utilize the full range and resolution with which said exposure

35 values are defined.

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37. The system of Claim 30 wherein said
means for weighting computes a mormalized weighted
summation in accordance with Bayes theorem of said K
distributions with said predetermined probability
5 distribution.

38. The system of Claim 21 wherein said
means for developing comprises means for developing
said latent and non-latent grains sequentially using
a different color dye for each.

10   39. The system of Claim 38 wherein said
latent and non-latent grains are developed with
positive and negative dyes, respectively, or
negative and positive dyes, respectively.

40. The system of Claim 27 further
15 comprising means connected to said means for
determining for weighting said distributions in
accordance with a predetermined probability
distribution of exposure values.

41. The system of Claim 40 wherein said
20 predetermined probability distribution of exposure
values defines the probability of any pixel in said
frame being exposed to a given exposure value.

42. A system for producing an enhanced
image from film which has been exposed to a user
25 image and to a plurality of K predetermined exposure
levels in K corresponding calibration patches, said
system comprising:

latent grain developing means for producing
a dye site of a first color at each latent grain in
30 said film;

non-latent grain developing means for
producing a dye site of a second color at each
non-latent grain in said film, whereby said latent
grain developing means and said non-latent grain
35 developing means together produce a two-colored

-40-

developed image;

scanner means for viewing said two-colored
developed image as an array of N picture elements
(pixels) and for determining, for each of said K

5   calibration patches, a dye amount D_p in each of
said N pixels of said first color, and a dye amount
D_n of said second color in said developed image;

first processor means responsive to said
scanner means for producing, for an ith one of

10   said K calibration patches, a distribution $P(D_n,$
$D_p|E_i)$ of a number of pixels having a particular
joint dye amount D_n, D_p, so as to produce an
ensemble comprising a plurality of K distributions;

second processor means responsive to said

15   first processor means for computing, for plural
joint dye counts
D_n, D_p in a range, a likeliest exposure value

$\overline{E}$ using a normalized weighted sum of products of
each of said distributions $P(D_n, D_p|E_i)$ with a

20   corresponding exposure level E_i;

means connected to said second processor
means for
storing a look-up table correlating each exposure

value $\overline{E}$ with a corresponding joint dye amount D_n,

25   D_p;

third processor means responsive to said
scanning means for determining from said look-up
table a likeliest exposure value corresponding to a
given joint dye count D_n, D_p for each pixel in

30   said user image so as to accumulate an array of
exposure values corresponding to an enhanced version
of said user image.

43.   The system of Claim 42 wherein said
first processor means comprises:

35

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fourth processor means for interpolating
among K of said distributions $P(D_n, D_p|E_i)$
where $1 \leq i \leq K$ so as to produce, as said
ensemble of distributions, M interpolated
distributions $P(D_n, D_p|E_j)$ where $1 \leq j \leq M$
and $M > K$, and

wherein said second processor means
computes a normalized weighted sum:

$$\bar{E}(D_p, D_n) = \sum_{i=1}^{M} E_i \ P(D_p, D_n \mid E_i) \ P(E_i) / $$

$$\sum_{i=1}^{M} P(D_p, D_n \mid E_i) \ P(E_i).$$

44. The system of Claim 43 wherein said
fourth processor means comprises:

means for computing, from said K
distributions, K corresponding values of:

$\bar{D}_p$, a mean value of D_p,

$\bar{D}_n$, a mean value of D_n,

S_{pp}, a variance of D_p,

S_{nn}, a variance of D_n, and

S_{pn}, a covariance of D_n and D_p;

means for interpolating M points among:

K mean values $\bar{D}_n$,

K mean values $\bar{D}_p$,

K variances S_{nn},

K variances S_{pp},

K covariances S_{pn};

means for computing, from said M
interpolated points, said M interpolated

-42-

distributions $P(D_n, D_p|E_j)$.

45. The system of Claim 42 further
comprising scratch suppression means, said scratch
suppression means comprising:

5   scratch detection means responsive whenever
a pixel is sensed in said user image having a joint
dye count D_n, D_p which, when substituted into
probability distributions for said exposure levels,
produces a number below a predetermined threshold,

10 for noting said pixel;

      scratch removal means responsive whenever
said scratch detection notes a given pixel in said
user image, for ignoring

15 a corresponding likeliest exposure value $\overline{E}$ stored in
said means for storing a look-up table, and instead
generating a likeliest exposure value by obtaining
from said means for storing a look-up table an
average exposure value of pixels surrounding said

20 given pixel but not including said given pixel.

46. The system of Claim 42 further
comprising means for scanning a plurality of known
images and determining therefrom an *a priori*
probability distribution of receiving a given

25 exposure level for a range of exposure levels
spanning an exposure latitude of said film, and
wherein each probability distribution in said second
processor means is weighted by said *a priori*
probability distribution.

30   47. A system for producing an enhanced
image from film which has been exposed to a user
image and to a plurality of K predetermined exposure
levels in K corresponding calibration patterns, said
system comprising:

35   latent grain developing means for producing
a dye site of a first color at each latent grain in

-43-

said film;

non-latent grain developing means for
producing a dye site of a second color at each
non-latent grain site in said film, whereby said
5 latent grain developing means and said non-latent
grain developing means together produce a
two-colored developed image;

scanner means for viewing said two colored
developed image;

10 first processor means responsive to said
scanning means for determining a probability
distribution $P(D_n, D_p|E_i)$ that a joint dye
amount D_n, D_p in one of said pixels was produced
by an exposure level E_i in a range corresponding
15 to said K predetermined exposure levels so as to
produce a plurality of probability distributions
$P(D_n, D_p|E_i)$;

second processor means responsive to said
first
20 processor means for determining a likeliest exposure
level $\overline{E}$ for a given joint dye count D_n, D_p, as a
normalized weighted sum of products of each of said
distributions $P(D_n, D_p|E_i)$ and a corresponding
one of said exposure levels E_i, for plural dye
25 counts D_n, D_p lying within a range;

look-up table means connected to said
second
processor means for storing a likeliest exposure
$\overline{E}$ with a corresponding joint dye count D_n, D_p;
30 means for addressing said look-up table
means with a joint dye count D_n, D_p from a pixel
in said user image sensed by said scanner means so
as to obtain a corresponding likeliest exposure
value so as to accumulate an array of exposure
35

-44-

values corresponding to an enhanced version of said
user image.

48. The system of Claim 47 wherein said
first processor means comprises:

5   third processor means for interpolating
among K of said distributions $P(D_n, D_p|E_i)$
where $1 \leq i \leq K$ so as to produce, as said
ensemble of distributions, M interpolated
distributions $P(D_n, D_p|E_j)$ where $1 \leq j \leq M$
10   and $M > K$, and

          wherein said second processor means
computes a normalized weighted sum:

$$\overline{E}(D_p, D_n) = \sum_{i=1}^{M} E_i P(D_p, D_n | E_i)P(E_i)/$$

15

$$\sum_{i=1}^{M} P(D_p, D_n | E_i)P(E_i).$$

49. The system of Claim 48 wherein said
20   third processor means comprises:

          means for computing, from said K
distributions, K corresponding values of:

          $\overline{D}_p$, a mean value of D_p,

25

          $\overline{D}_n$, a mean value of D_n,

          S_{pp}, a variance of D_p,
          S_{nn}, a variance of D_n, and
          S_{pn}, a covariance of D_n and D_p;
30   means for interpolating M points among:

          K mean values $\overline{D}_n$,

          K mean values $\overline{D}_p$,
          K variances S_{nn},
35   K variances S_{pp},

-45-

K covariances S_{pn};

means for computing, from said M interpolated points, said M interpolated distributions $P(D_n, D_p|E_j)$.

5   50. The system of Claim 47 further comprising scratch suppression means, said scratch suppression means comprising:

scratch detection means responsive whenever a pixel is sensed in said user image having a joint

10 dye count D_n, D_p which, when substituted into probability distributions for said exposure levels, produces a number below a predetermined threshold, for noting said pixel;

scratch removal means responsive whenever

15 said scratch detection notes a given pixel in said user image, for ignoring a corresponding likeliest exposure value

$\overline{E}$ stored in said means for storing a look-up table, and instead generating a likeliest exposure value by

20 obtaining from said means for storing a look-up table an average exposure value of pixels surrounding said given pixel but not including said given pixel.

51. The system of Claim 47 further

25 comprising means for scanning a plurality of known images and determining therefrom an a priori probability distribution of receiving a given exposure level for a range of exposure levels spanning an exposure latitude of said film, and

30 wherein each probability distribution in said second processor means is weighted by said a priori probability distribution.

35

FIG.1

FIG. 2

FIG. 3
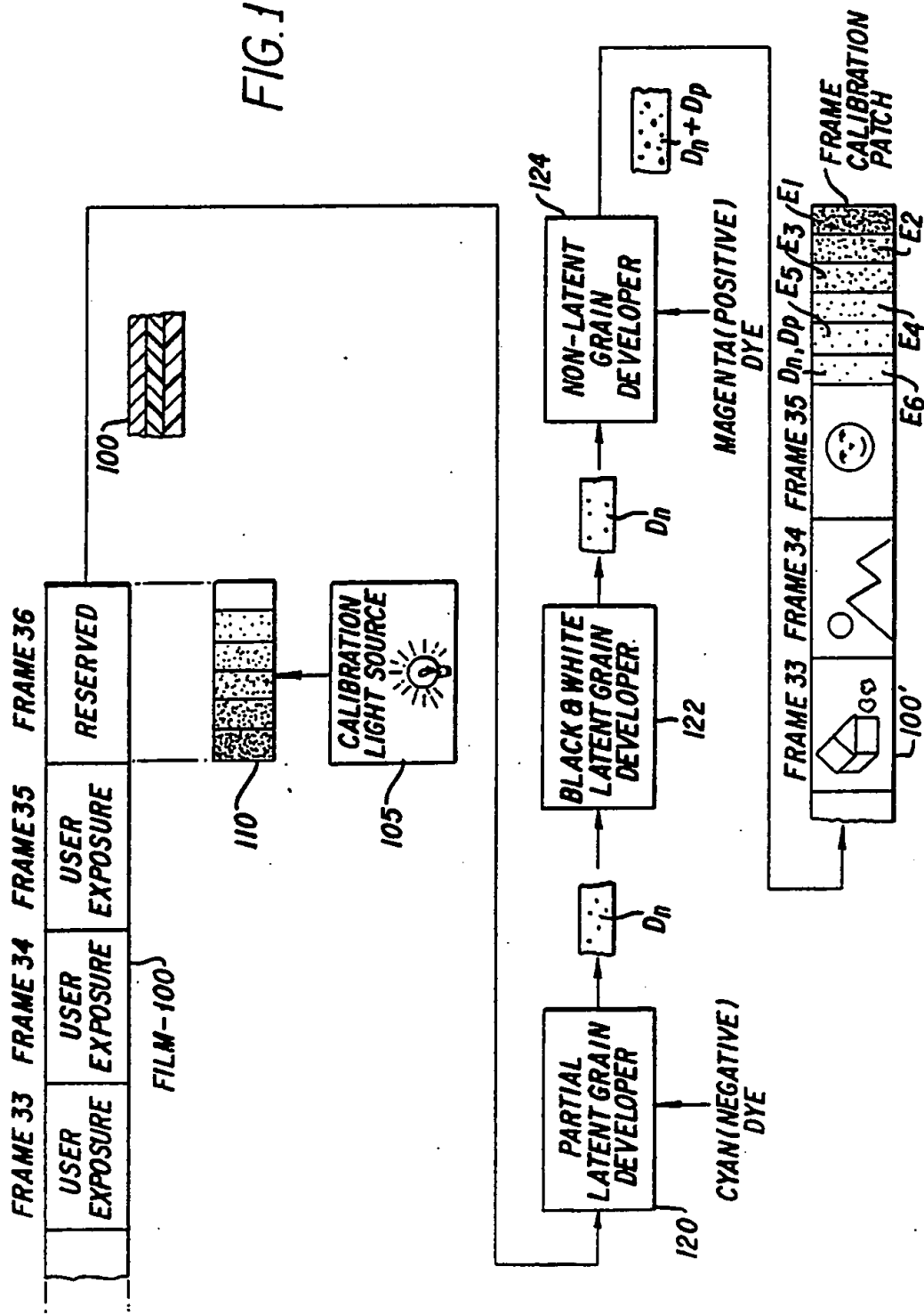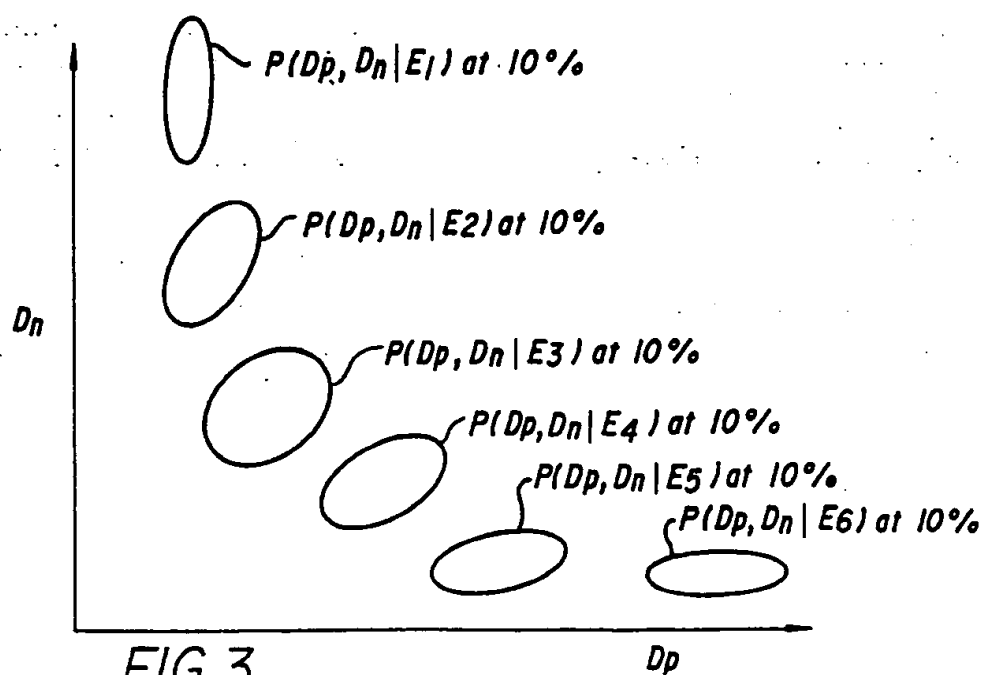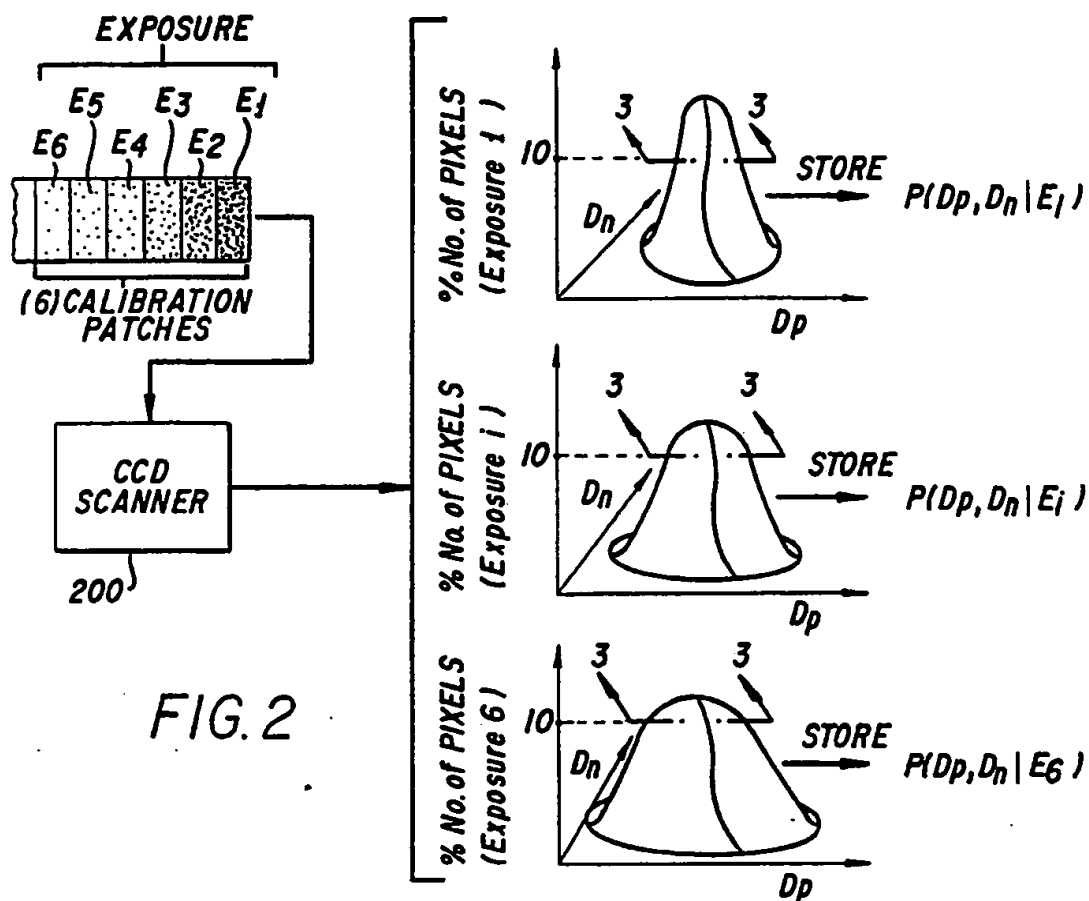
DETERMINE LIKLIEST EXPOSURE $\bar{E}$ FOR EACH POSSIBLE COMBINATION OF D_n AND D_p :

$$\bar{E}(D_n, D_p) = \frac{\sum\limits_{i=1}^{m} E_i \, P(D_n, D_p \mid E_i) \, P(E_i)}{\sum\limits_{i=1}^{m} P(D_n, D_p \mid E_i) \, P(E_i)}$$

(s)

$(m = \text{No. of CALIBRATION EXPOSURES})$

STORE THE RESULTS IN A LOOK-UP TABLE

SCAN A USER IMAGE ON THE FILM PIXEL-BY-PIXEL
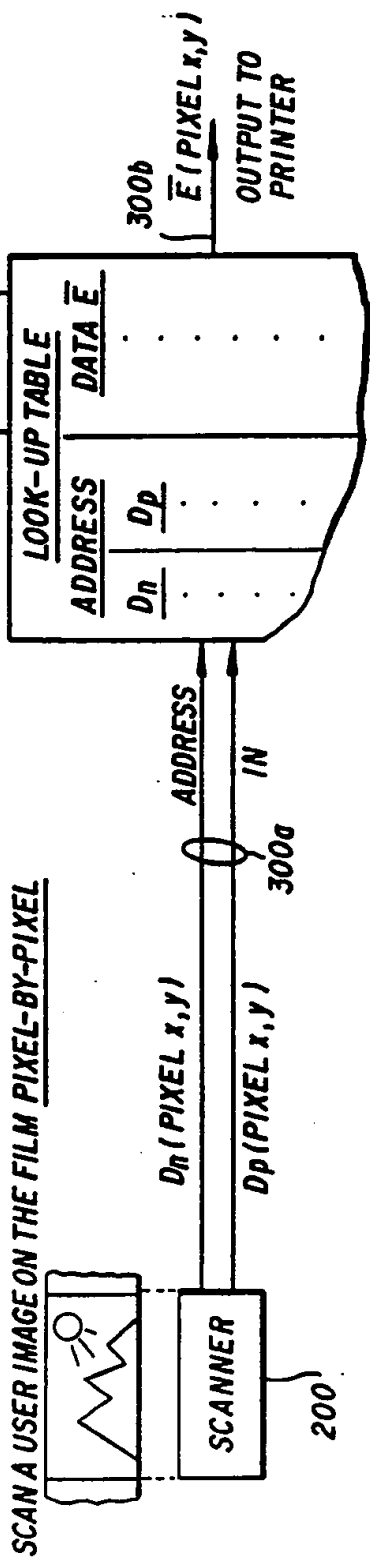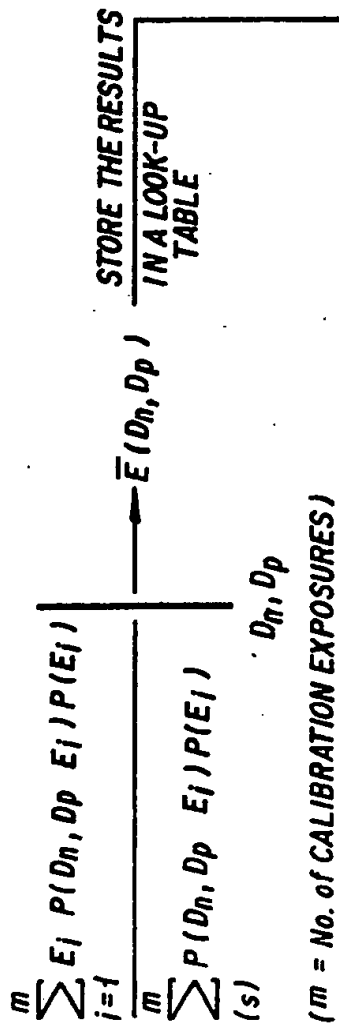
FIG. 4

FOR i = 1-6 (Six Calibration Exposures) $\qquad$ *FIG. 5*

$\underline{\text{COMPUTE FOR EACH i}}$

$\underline{MEAN}$
(a) $\bar{D}_n(E_i) = \frac{1}{N}\sum_{j,k} D_n(j,k;E_i)$

N = Number of pixels in calibration patch
j, k index the pixels
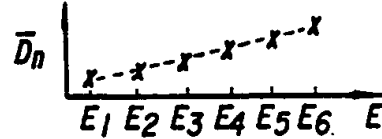
$\underline{MEAN}$
(b) $\bar{D}_p(E_i) = \frac{1}{N}\sum_{j,k} D_p(j,k;E_i)$
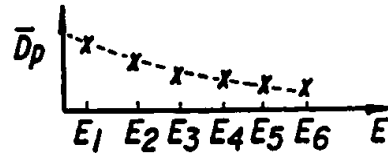
$\underline{COVARIANCE}$ *(also called variance)*
(c) $S_{nn}(E_i) = \frac{1}{N-1}\sum_{j,k}\left[D_n(j,k;E_i)-\bar{D}_n(E_i)\right]\left[D_n(j,k;E_i)-\bar{D}_n(E_i)\right]$
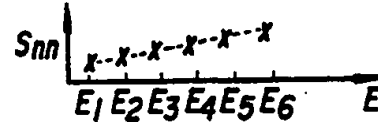
$\underline{COVARIANCE}$ *(also called variance)*
(d) $S_{pp}(E_i) = \frac{1}{N-1}\sum_{j,k}\left[D_p(j,k;E_i)-\bar{D}_p(E_i)\right]\left[D_p(j,k;E_i)-\bar{D}_p(E_i)\right]$
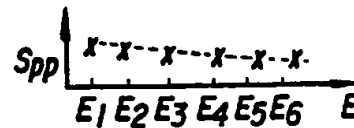
$\underline{COVARIANCE}$
(e) $S_{pn}(E_i) = \frac{1}{N-1}\sum_{j,k}\left[D_p(j,k;E_i)-\bar{D}_p(E_i)\right]\left[D_n(j,k;E_i)-\bar{D}_n(j,k;E_i)\right]$
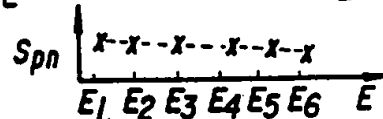
THEN: Divide the horizontal axis (E) into 255 segments
between 256 points E_m (m = 1,.....,256)
FOR EACH E_m, INTERPOLATE VALUES

$\bar{D}_n(E_m)$, $\bar{D}_p(E_m)$, $S_{nn}(E_m)$, $S_{pp}(E_m)$, $S_{pn}(E_m)$

By an interpolation technique such as linear interpolation
or quasi-cubic Hermite interpolation
THEN USING MULTIVARIATE GAUSSIAN PROBABILITIES,

(f)
$$P(D_p, D_n \mid E_m) = \left[2\pi\, DET\begin{pmatrix}S_{pp} & S_{pn}\\ S_{pn} & S_{nn}\end{pmatrix}\right]^{-\frac{1}{2}} exp\left[-\frac{1}{2}\begin{pmatrix}D_p-\bar{D}_p(E_m)\\ D_n-\bar{D}_n(E_m)\end{pmatrix}^T\begin{pmatrix}S_{pp} & S_{pn}\\ S_{pn} & S_{nn}\end{pmatrix}^{-1}\right.$$

$$\left.\begin{pmatrix}D_p-\bar{D}_p(E_m)\\ D_n-\bar{D}_n(E_m)\end{pmatrix}\right]$$

SUBSTITUTE SHEET
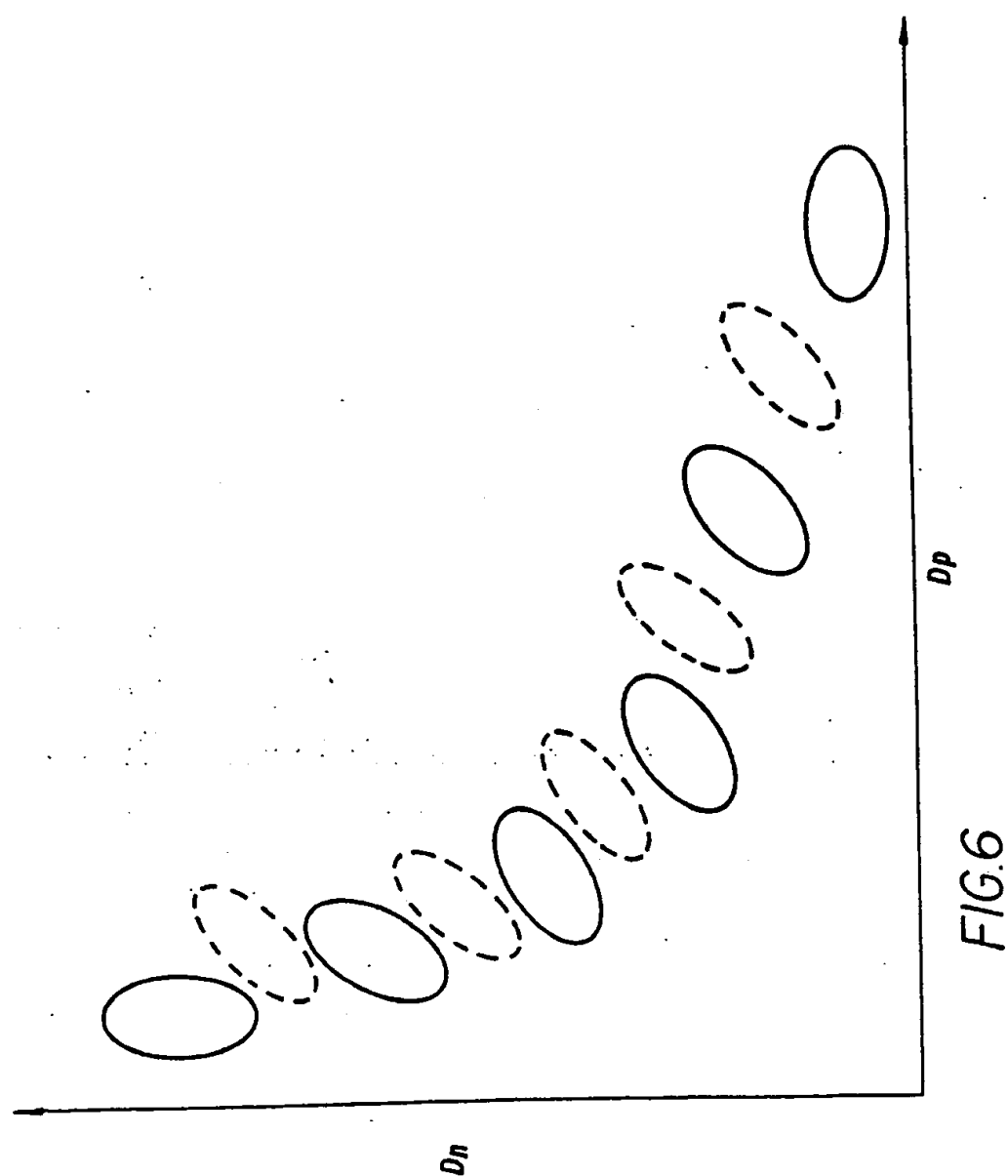
FIG.6

FIG.7
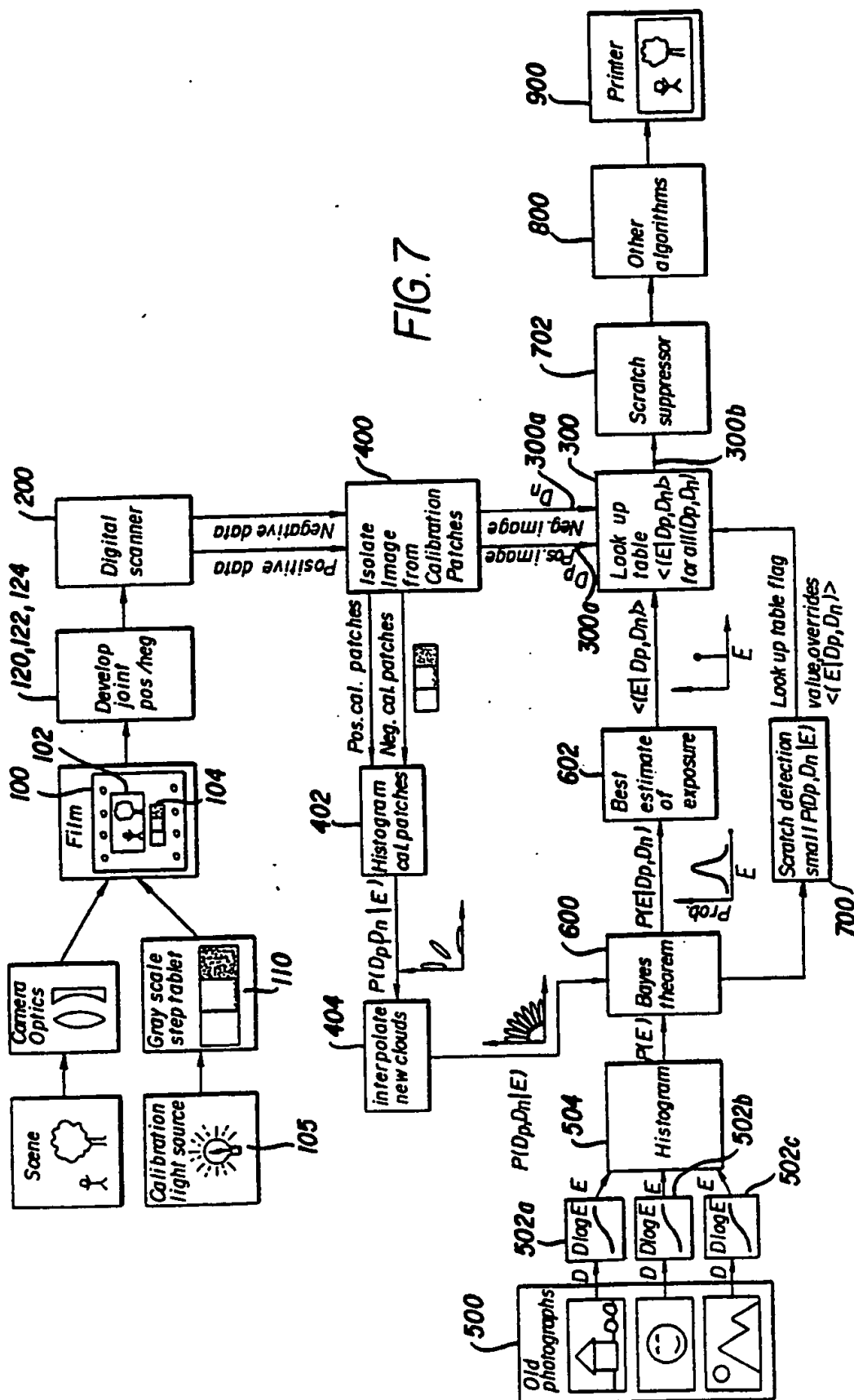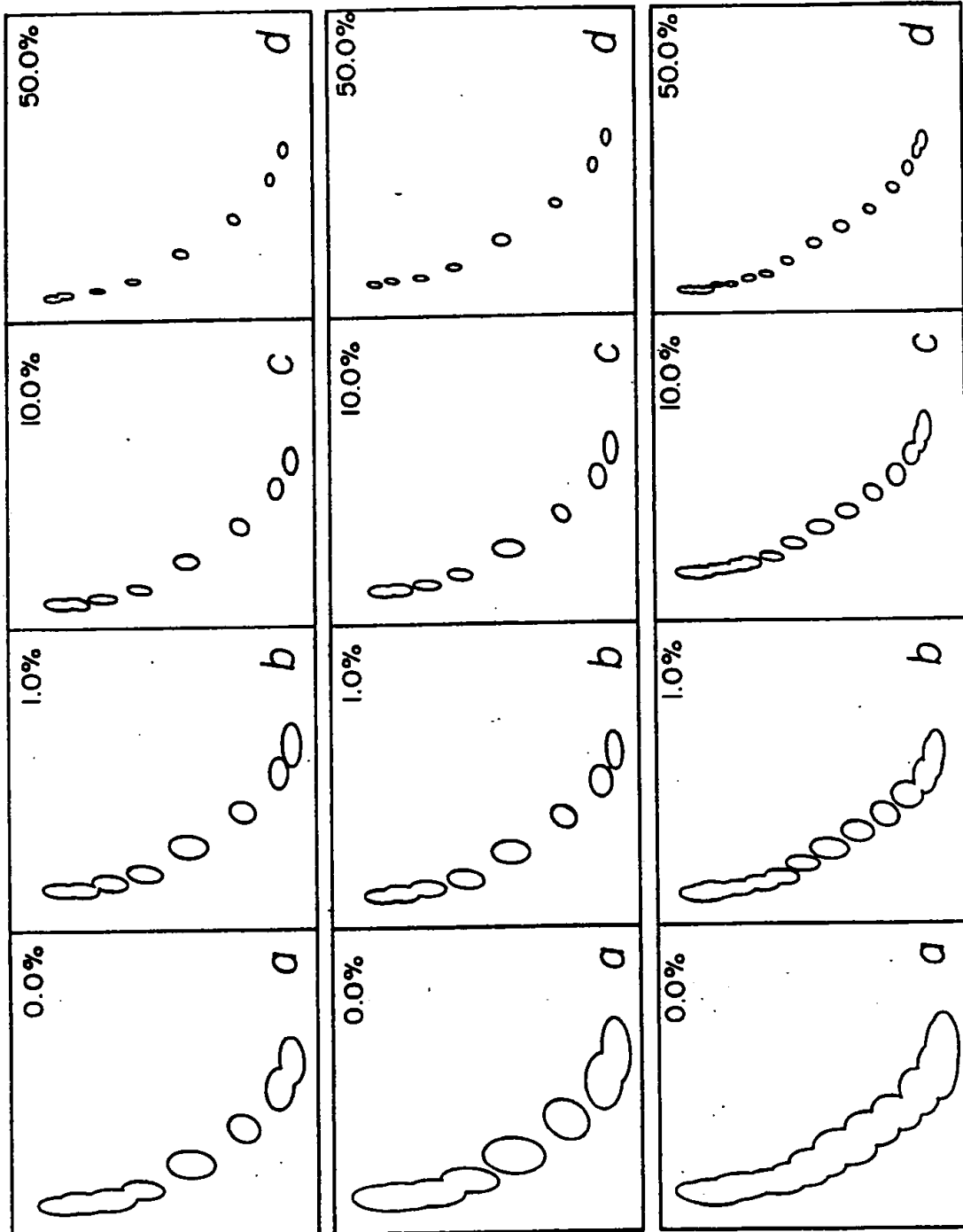
FIG.8
(a-d)

FIG.IO
(a-d)

FIG.9
(a-d)

INTERNATIONAL SEARCH REPORT

International Application No **PCT/US 89/03052**

<table>
<tr><td colspan="3">I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) ⁶</td></tr>
<tr><td colspan="3">According to International Patent Classification (IPC) or to both National Classification and IPC</td></tr>
<tr><td colspan="3">IPC⁵: H 04 N 1/40</td></tr>
</table>

<table>
<tr><td colspan="2">II. FIELDS SEARCHED</td></tr>
<tr><td colspan="2" align="center">Minimum Documentation Searched ⁷</td></tr>
<tr><td>Classification System</td><td align="center">Classification Symbols</td></tr>
<tr><td>IPC⁵</td><td>H 04 N</td></tr>
<tr><td colspan="2" align="center">Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched ⁸</td></tr>
<tr><td colspan="2"></td></tr>
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<table>
<tr><td colspan="3">III. DOCUMENTS CONSIDERED TO BE RELEVANT ⁹</td></tr>
<tr><td>Category [*]</td><td>Citation of Document, ¹¹ with indication, where appropriate, of the relevant passages ¹²</td><td>Relevant to Claim No. ¹³</td></tr>
<tr><td>A</td><td>Photographic Science and Engineering, vol. 22, no. 6, November/December 1978, Society of Photographic Scientists and Engineers (Springfield, US), G.R. Bird: "Normal development, reversal development, and composite processing: a new method for gaining a simultaneous improvement in latitude and detective quantum efficiency in silver halide films", pages 328-335, see the whole document

cited in the application</td><td>1,21,42,47</td></tr>
<tr><td>A</td><td>Proceedings of the International Conference on Electronic Image Processing, 26-28 July 1982, P.G. Powell et al.: "A method for the digital enhancement of unsharp, grainy photographic images", pages 179-183, see the whole article</td><td>1,21,42,47</td></tr>
<tr><td>A</td><td>WO, A, 87/02852 (EASTMAN KODAK) 7 May 1987, see abstract; page 11, line 16 - ./.</td><td>1,21,42,47</td></tr>
</table>

* Special categories of cited documents: ¹⁰
"A" document defining the general state of the art which is not considered to be of particular relevance
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<table>
<tr><td colspan="2">IV. CERTIFICATION</td></tr>
<tr><td>Date of the Actual Completion of the International Search

20th September 1989</td><td>Date of Mailing of this International Search Report

3 0. 10. 89</td></tr>
<tr><td>International Searching Authority

EUROPEAN PATENT OFFICE</td><td>Signature of Authorized Officer

T.K. WILLIS</td></tr>
</table>

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category*	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No
	page 13, line 1 --	
A	DE, A, 3402823 (H. BERTHOLD AG) 25 July 1985, see page 7, line 33 - page 10, line 14 ----	1,21,42,47

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on 18/10/89
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Patent document cited in search report	Publication date	Patent family member(s)		Publication date
WO-A- 8702852	07-05-87	US-A- EP-A- JP-T-	4677465 0250468 63501251	30-06-87 07-01-88 12-05-88
DE-A- 3402823	25-07-85	None		